

Improving Methods for Estimating Fatality of Birds and Bats at Wind Energy Facilities in California

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Introduction

California pioneered large-scale wind energy development beginning in the 1970s. As a clean, renewable energy resource, wind energy holds great promise provided that it can be sited and developed in such a way as to reasonably avoid and (if necessary) mitigate impacts on already stressed wildlife resources. To this end, wind energy and wildlife stakeholders have collaborated to survey avian/bat activity and study the impacts of wind project operations, and policymakers have incorporated research protocols into the permitting process.

In 2007, the California Energy Commission (CEC) and California Department of Fish and Game released California Guidelines for Reducing Impacts to Birds and Bats from Wind Energy Development¹ (the Guidelines) to provide recommended protocols for assessing and minimizing impacts from wind energy development to birds and bats. The Guidelines recommend protocols for assessing, evaluating, and determining the effects of wind projects on birds and bats, and also recommend impact avoidance, minimization, and mitigation measures. In addition, the Guidelines provide an equation that can be used to adjust for survey error the number of bird (or bat) carcasses that are visually observed during an environmental monitoring survey of a wind facility. The equation, which can be found in Appendix F of the Guidelines, adjusts for survey errors resulting from the inability of an observer to locate all carcasses on the survey plot at the time of observation, and for the probability of scavenger removal prior to the time of observation.

The California Wind Energy Association (CalWEA) submitted a request for, and was subsequently awarded, a grant from the CEC to rigorously evaluate the procedures provided in the Guidelines for estimating mortality of birds and bats associated with collisions with wind turbines in California. Information gathered from this study will be directly applicable to wind development projects in California, and, the fundamental principles evaluated and discovered in this project may be applicable to wind development in other parts of the US and Europe.

This Research Plan lays out the goals of CalWEA's project and reviews the equations used to adjust mortality observations currently found in the literature. It describes the site selected for study, provides an experimental design for evaluating and testing approaches for estimating the true bird and bat mortality at a wind facility based on observational evidence of collision mortality, and outlines a data collection and quality assurance (QA) plan.

¹ California Guidelines for Reducing Impacts to Birds and Bats from Wind Energy Development. 2006. California Energy Commission. Sacramento, CA.

Project Goals

The primary goal of this project is to generate information that will enable the comparison of existing mortality estimation methods and the development of advanced models. The equations and models will be applied to the observed data generated during this study, and the model predictions will be compared and evaluated against the true mortality at the experimental location. Data generated by this project also will be able to be used to provide insights into several other issues that are important to risk assessments of wind facilities. Specifically, this project will generate information that can be used to:

- 1) Compare existing mortality estimation methods.
- 2) Develop advanced models that link observational data with measurements of ecological condition.
- 3) Test and evaluate the shape of carcass removal curves (or scavenging curves) under a variety of environmental conditions.
- 4) Evaluate the effect of time-dependency on the probability of bird and bat scavenging and removal.
- 5) Evaluate the relationship of survey error with other factors, such as density of the carcasses on the ground at the time of observation, whole or partial carcass remains, and environmental conditions.

Once the project's research team evaluates the data, and tests existing models or creates new models, we will provide general guidance for (1) generating site-specific data used to parameterize equations, (2) selecting existing or new equations based on site-specific conditions, and (3) interpreting the results generated by the statistical methods.

Mortality Estimation Equations

Various equations have been proposed for estimating the true mortality at a wind facility based on observational data collected during a monitoring survey. The experiments described in this document will provide information that can be used to better parameterize the existing equations, or lead to new models and equations for estimating the true site-specific mortality.

The equations found in the literature take various mathematical forms, but require (to varying degrees) similar types of data: number of observed birds (or carcasses, partial carcasses e.g. feathers, etc.) at a specific time and location, interval since the last survey at the location, a measure of searcher efficiency, an estimate of the carcass removal rate, or an estimate of the scavenger efficiency as a function of time. Therefore, at a minimum the experimental design must collect these data, or information leading to the calculation of these variables, in order to test and evaluate the various equations.

Below is a listing of the equations this project will evaluate, followed by a list of comments concerning the limitations of these existing equations, including the procedures used to parameterize the equations using field trials of generally short duration. If additional equations are found, we will include them in our analysis.

Schoenfeld² (and as cited in Erickson et al.³) provides a review of several equation forms, including the following which are evaluated using simulation:

1)

$$m_{ij} = \frac{I_{ij}C_{ij}}{t_{ij}p_{ij}}$$

2)

$$m_{ij} = \frac{I_{ij}C_{ij}}{t_{ij}p_{ij}} \left(\frac{e^{I_{ij}/t_{ij}} - 1 + p_{ij}}{e^{I_{ij}/t_{ij}} - 1} \right)$$

The CEC *Guidelines* Appendix F⁴ presents an alternative form that was proposed by Dr. Ken Pollock of North Carolina State University:⁵

3)

$$m_{ij} = \frac{C_{ij}}{s_{ij}p_{ij}}$$

Smallwood⁶ modifies equation 3 to adjust for scavenging over time, which is used in the Altamont 2008 Monitoring Report:⁷

4)

$$m_{ij} = \frac{C_{ij}}{s_{ij}^*p_{ij}}$$

Huso^{8, 9} used simulation to evaluate the following equation:

5)

$$m_{ij} = \frac{C_{ij}}{s_{ij}p_{ij}e_{ij}}$$

² Schoenfeld, P. 2004. Suggestions Regarding Avian Mortality Extrapolation, unpublished report to West Virginia Highlands Conservancy, Davis, WV.

³ Erickson, W. P., J. Jeffrey, K. Kronner, and K. Bay. 2004. Stateline Wind Project Wildlife Monitoring Annual Report, Results for the Period July 2001 B December 2003, report submitted to FPL Energy, the Oregon Office of Energy, and the Stateline Technical Advisory Committee.

⁴ <http://www.energy.ca.gov/windguidelines/index.html>

⁵ Dick Anderson, personal communication.

⁶ Smallwood, K. S. 2007. Estimating wind turbine-caused mortality. *Journal of Wildlife Management*, 71(8), pp. 2781-2801.

⁷ http://www.altamontsrc.org/alt_doc/m21_2008_altamont_bird_fatality_report.pdf

⁸ Huso, M. P. 2010. An Estimator of Wildlife Fatality From Observed Carcasses. *Environmetrics*. Published online in Wiley InterScience (www.interscience.wiley.com).

⁹ <http://www.nationalwind.org/pdf/HusoManuela.pdf>

Where:

m_{ij} = true number of dead birds at turbine i in interval j

C_{ij} = number of carcasses counted at turbine i at the end of interval j

p_{ij} = measure of searcher efficiency, representing the proportion of carcasses found by searchers during a survey as estimated by searcher detection trials

I_{ij} = length (days) of the search interval

t_{ij} = average number of days a carcass will persist unscavenged (usually considered the same for all turbines, but not all intervals)

s_{ij} = estimate of the carcass removal rate, as measured by the proportion of carcasses remaining since the last search

s_{ij}^* = carcass removal rate as a function of time

e_{ij} = effective interval = $-\log(0.01) * \text{avg. removal time}$

Other available methods calculate the potential incremental increase due to various sources of bias (e.g., search, removal, habitat, and crippling bias), and use a linear additive model e.g., Gauthreaux¹⁰) to estimate true mortality.

The observer error and scavenging terms in the above equations are typically estimated from independent field trials of a fixed length. The trials can be conducted prior to wind project operation, or during the course of operations. Each of the above equations has both advantages and disadvantages with respect to simulating the process of finding birds at wind turbine sites. While some of the equations have been evaluated using computer simulation, none of the equations have been rigorously tested for precision and accuracy using experimentally designed and rigorous field studies.

Site Description

The study will be implemented at the Altamont Pass Wind Resource Area (APWRA), located in central California approximately 56 miles (908 kilometers) east of San Francisco.



The Altamont landscape consists of rolling hills ranging mostly between 150 and 300 feet (61-91 m) in elevation above sea level. The Natural Communities and Land Cover Types identified in the Natural Community Conservation Plan (NCCP) for the Altamont Pass Wind Resource Area include agricultural land, annual grassland, alkali grassland, seasonal wetlands, alkali wetlands, perennial wetlands and ponds, riparian woodland and streams, chaparral, and oak woodland.

Differential air temperatures between the warmer Central Valley east of Altamont Pass and the cooler marine air from San Francisco Bay cause steady winds of 15–30 miles per hour (25–45

¹⁰ Gauthreaux, S. A. 1995. Suggested Practices for Monitoring Bird Populations, Movements, and Mortality in Wind Resource Areas. Proceedings of National Avian-Wind Power Planning Meeting, Denver, CO, 1994.

kilometers per hour) to blow across the APWRA during the mid-afternoon and evening periods between April and September. Winter wind speeds average 9–15 miles per hour (15–25 kilometers per hour). The spring and summer high wind period is when 70–80% of the wind turbine power is generated in the APWRA.¹¹

Permits have been granted for 5,400 wind turbines in the APWRA, rated at a capacity of approximately 580 megawatts (MW), distributed over 50,000 acres (150 square kilometers) of rolling grassland hills and valleys. Turbines are arrayed along ridgelines and other geographic features in *turbine strings*. These turbines were not installed all at once; rather they were brought online in a series of projects. These projects typically share a common turbine type, geographic location, and owner/operator, and have been classified as *operating groups* for the purposes of this study. The number of functional turbines varies over time as a result of mechanical breakdowns, maintenance, seasonal and weather-related shutdowns, and strategic turbine removals designed to reduce turbine-related avian mortality. The actual number of turbines available at any one time for power generation is expected to range from 4,500 to 5,000.

The APWRA supports a broad diversity of resident, migratory, and wintering bird species that regularly move through the wind turbine area.¹² Diurnal raptors (eagles and hawks), in particular, use the prevailing winds and updrafts for soaring and gliding during daily movement, foraging, and migration. Birds passing through the rotor plane of operating wind turbines are at risk of being injured or killed. Multiple studies of avian fatality at the APWRA show that golden eagles, red-tailed hawks, American kestrels, burrowing owls, barn owls, and a diverse mix of small birds or non-raptor species are killed each year in turbine-related incidents.¹³ All the native species are protected by either or both federal and state wildlife legislation.

The geographical unit of interest from an experimental perspective at the Altamont is a turbine string or a line of turbines. The Altamont has available to our study over 800 turbine strings. Over 400 of these strings are currently monitored on a regular basis (note: the number of turbine strings may change starting in October 2010). The monitored strings are located over the extent of the APWRA's 60 square miles, and therefore cover a variety of ecological conditions.

Experimental Design

This section describes key issues associated with the proposed experimental design. The narrative initially describes the design, and follows with information on key issues that affect the implementation of the design and that impact the logistics of the project.

Broad Overview of Experimental Design

The project will collect data at 30 wind turbine “strings,” considered the experimental units. A group of six turbine strings will be simultaneously observed during any time period; this group of six strings is termed a block. Therefore, the entire experiment will consist of five blocks of six strings per block. Observations made at any block will be finished before the start of

¹¹ Smallwood and Thelander 2004.

¹² Orloff and Flannery 1996.

¹³ Howell and DiDonato 1991; Orloff and Flannery 1996; Howell 1997; Smallwood and Thelander 2004.

observations at the next block of strings. The number of individual turbines in a string in the APWRA can vary from three to as many as seventeen, but the majority of strings consist of approximately seven to eight turbines. Each string within a block will be observed for up to six weeks, or until no marked birds or bats remain on the string. The entire study period for the project field trial will be approximately 30 weeks (5 blocks times up to 6 weeks of observation per block, with allowances for holidays and personnel unavailability). Two strings in blocks 2 and 3 will be randomly designated as controls, with no marked carcasses placed. Therefore, data for model comparison and model development will be taken from twenty-eight total strings.

At the beginning of the observation period for each sampling block, one of two Project Field Managers (PFMs) will randomly place a fixed number of uniquely marked birds and bats at each of the six strings comprising that sampling block. In order to maximize sampling efficiency, both birds and bats will be placed at the same string. The objective is to both observe the removal of birds and bats as a result of scavenging, and to generate observations reflecting monitoring error.

A PFM will visit the strings daily for fourteen days and record the position and character (i.e., body parts) of all carcasses remaining at the string. After the initial fourteen day period, a PFM will also visit each string every other day for the remaining of the block study period. Therefore, a PFM will visit each string with marked carcasses a total of twenty-eight times over a six week period. The PFMs will visit each string either during the evening or early morning, depending on the number of daylight hours available.

Three separate independent observers will visit each string, at approximately two week intervals. The observers will be blind to the location of carcasses. An individual observer will visit a specific string only once during the block study period. Therefore assuming that an individual observer can visit two strings per day, a minimum of three independent observers are needed for the project. The observers will walk the strings using a standardized protocol (below). The observers will identify observed birds and bats as “study carcasses” based on the markings. At the site of each observed study carcass, the observers will record the ecological conditions within a two-foot area around the found carcass (details described below). Carcasses will not be removed by the observers. All observers will be given explicit instructions on survey techniques, including instructions to ignore any pre-search information on the existence of birds or bats on the string. And, the observers will be informed that some strings will have no marked bird or bat carcasses, therefore, surveys will be conducted without the pre-conception that marked carcasses should be on the ground. In addition, the observers will be informed that the string may not have marked carcasses due to the presence of control strings. Strings will be selected such that the level of effort among observers is similar (i.e., the number of turbines and geographic area of the string is consistent). Given the above, a total of eighty-four observation days (28 strings times three observations per string) of data will be generated by the observers.

Below is a representation of the experiments that are planned for this study. The number of birds or bats per string was chosen as a representative of the expected daily maximum true mortality at wind facilities in California. Examination of the APWRA Scientific Review Committee (SRC) current avian monitoring study indicates that the total number of birds (of any species) found during any one survey on any string ranges from zero to eleven, with some surveys resulting in observations of five to nine birds. We realize that during average string surveys at the Altamont,

few if any birds are generally observed. However, in order to test the hypothesis associated with the relationship between survey error and bird density, the experiments need to begin with a representative high value, which is considered to be fifteen bird carcasses. In addition, one of the five blocks will be implemented with thirty bird carcasses. This block will provide information on survey error with extreme events, or survey error at sites with larger mortality. In addition, this block will provide information from which density effects can be evaluated. Fewer bat carcasses will be placed in this block, in order to limit the total number of carcasses present.

Block Number	Control String Included	Starting number of birds per string (except control)	Starting number of Bats per string (except control)	Total Number of Birds	Total Number of Bats
1	N	15	12	90	72
2	Y	15	12	75	60
3	Y	15	12	75	60
4	N	15	12	90	72
5	N	30	10	180	60
Total				510	324

If the project’s labor budget allows, additional blocks will be added.

Ecological Variation and String Selection

Selection of string locations for this study is a function of (1) efficient labor management, and (2) the ecological characteristics of the string location (e.g., low or high grass area, grazed area, etc.). In addition, the CalWEA study must coordinate string selection with the on-going monitoring activities at the Altamont. The SRC monitoring team (MT) may ultimately be included in the collection of data at specific strings (discussion below). However, coordination between the CalWEA study and the MT activities is expected to occur with respect to string selection during specific time periods and as described below, but we are currently assuming that no explicit merging of field activities will occur.

Ecological variation associated with specific wind turbine development locations within the State of California is an important consideration in the design of the experiments and selection of specific strings for use in the study. Variation in habitat condition is considered a key variable affecting the change in survey error among locations. Variation in vegetation type and density, scavenger species and associated activity levels, climate conditions, geographic conditions associated with turbine placement, and a host of other site-specific variables could influence the overall survey error rate for a specific site.

Within each string at the Altamont, the ecology is somewhat variable. For example, areas surrounding a string may contain vegetation of various heights, including barren areas. Therefore, it is generally difficult to characterize a string explicitly as a “high grass” or “low grass” area, for example. We note, however, that grass height is a function of season, geographic

area of the Altamont, and activity in the area (e.g., cattle grazing). Given the large geographical area covered by the Altamont, the within-string ecological characteristics at a particular time of year will have a somewhat, if not exact, consistent ecological condition (except, for example, where roads bisect the string search area).

Strings will be selected to (1) maximize ecological variation and coverage, and (2) to minimize labor hours required for the CalWEA survey crew to gain access to the geographical areas. To maximize labor management, strings selected for experimentation will generally be within close proximity to each other, sharing road access to minimize travel time. Based on the proposed experimental design, six strings (comprising a block) will be simultaneously used in the experiment. Selection of strings for each specific block will be based on the criteria mentioned above. Because within any given string the ecological variation can be significant, string selection will be principally driven by project and labor management considerations. The observers and field managers must be able to access the block easily and quickly in order to maximize the amount of data that can be obtained from any given set of observations.

At the Altamont, strings are given numbers, termed a string number, to identify specific strings and locations. To the degree possible, strings comprising a single block will be selected such that the topography, ecology, and vegetation are similar. And, to the degree possible, subsequent blocks of strings will be selected such that the between-block topography, ecology, and vegetation are different than other blocks.

Actual selection of specific string numbers will be made in coordination with the ongoing MT activities to the extent possible and will be determined during the pilot study. The PFMs selected for this project will work in concert with the on-going SRC surveys to select strings and blocks such that a large degree of ecological variation is achieved among the strings. Selection of string numbers for any block will occur just prior to implementing the field activities, and will be the responsibility of the PFMs.

Process for Marking, Distributing, and Observing Carcasses

The PFMs are responsible for marking and distributing all birds and bats employed during the field activities of this project.

Study birds' appendages will be marked with unique tape color, and flight feathers will be clipped. Bats' appendages will be taped. Trial bird identifiers can be written on the taped appendages but after scavenging actions, tape can easily be removed by scavengers. Careful tracking of carcass positions and the detection of cut flight feathers will be the most reliable ways of identifying carcasses as trial birds. In some cases, particularly over time at a specific string, whole bird carcasses may be torn into various body parts.

Tracking the position of trial carcasses will involve recording the distance and bearing to the closest turbine, as well as using a GPS with sub-meter accuracy. As the carcasses age, they may fragment due to scavenging actions and weather conditions (e.g. wind, sun and rain). When the PFMs check the study carcasses on a daily basis, he or she will continue to update the position of the carcasses as well as carcass condition. The PFMs will be able to identify trial birds and bats

used in the study based on species-specific characteristics and initial marking procedures. The PFMs will attempt to track and record individual body parts throughout the six week observation period for a specific block. If all carcasses are removed on an individual string before six weeks, the PFMs will stop observations on that specific string.

The placement of whole bird and bat carcasses on a specific string will begin the observation period (day zero). Three observations periods are planned for each string within a block. The timing of the observations within the six-week period is critical. The objective is to distribute the observations over the six week observation interval so that a varying number of carcasses are on the plot at the time of observation. The actual number of the plot will be known to the PFMs, but unknown to the blind observers. The rate at which carcasses will be removed from the strings is unknown, and the generation of removal curves under varying condition is one of the objectives of this study. During the pilot study phase of this project, timing of the observation days will be evaluated. As the study progresses, changes in the timing of the observation days within the six week observation window may occur in order to maximize the variability in carcasses on the ground at the time of observation.

Figure 1 illustrates the issue with the carcass placement date and subsequent observations. For any given string, the actual shape of the removal curve is unknown, and evaluating the degree of variance in the curve shape (or statistical parameters of the underlying distribution from which the curve is derived) is one of the goals of the project. Finding appropriate placement dates prior to knowing the removal curve such that a range of carcass density is studied is part of the initial pilot study, and the interval between subsequent observation days may change over time.

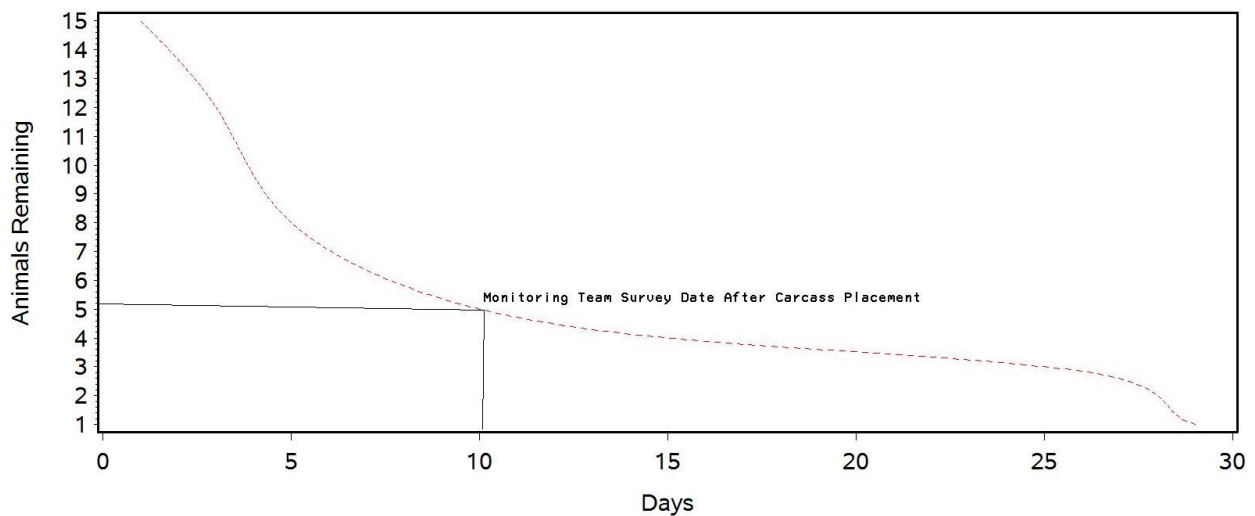


Figure 1. Hypothetical Representation of Carcass Removal over Six Weeks

At the Altamont, most strings are located on ridge lines. The search area for each string will extend 50 meters out from individual turbines comprising the string, on all sides. During each survey, mortality search transects will be walked within the string search area during which the searcher scans the ground for bird and bat carcasses and/or parts of carcasses such as feathers and bones. The distance between transects within each search area will average seven meters depending on the terrain, height of the vegetation, and the height of the individual searcher. When evidence of a fatality is found, the location of the find will be marked with flagging, and the searcher will then

continue to search the remaining area. After completing the search, the observer will return to each flagged location to record data on all the finds. Recorded data is explained below.

An additional issue that will be studied, and is affected by the timing of observations, is the effect of carcass age on observer error. Carcass age is expected to influence scavenger removal rates, but may also affect observer detection probability. As an un-scavenged carcass ages it becomes may become less attractive to scavengers, reducing the chance for scavenging actions that may either remove the carcass completely or fragment the carcass, spreading signs of the carcass over the plot. Also as a carcass ages, if it is not removed, the chance that it will be fragmented by scavenging actions increases, possibly affecting the probability of observer detection. Once a carcass is scavenged and not removed, it may slowly degrade from abiotic mechanisms (wind and rain). This can reduce observer detection probability and can eventually remove all significant signs of the carcass. So, in general as a carcass ages, removal rates may decrease and then eventually increase slowly as the carcass degrades. Observer detection probability may initially increase as a carcass ages and fragments, but as the carcass ages further and degrades, observer detection probability may also decrease.

Therefore, under the direction of the PFMs, the timing of observations within the six week interval will consider carcass age. Timing will be adjusted to ensure that both fresh and older carcasses remain on the string for possible observation. The observers will not remove carcasses as they are detected, therefore, the impact of carcass age on the shape of the carcasses removal curves can be evaluated during the data analysis phase of the project.

Surveys will not be conducted if there is heavy rain or fog that would unduly influence detection probability among individual observers.

Species Selection

Carcass size is a key variable that influences both the observer detection probability and scavenger removal rate. Generally, larger birds (e.g., golden eagles) are reported to have smaller survey error rates than smaller birds (or bats). The smaller birds and bats are more difficult to see over large distances, and may be more easily covered by vegetation. Also, smaller animals are more subject to complete removal by scavengers.

This study will focus on smaller animals. The cowbird (*Molothrus ater*) and bat (species to be determined) are the current species of choice. To date, approximately one thousand cowbirds and three hundred bats have been located and are being shipped to the NextERA facility located at the Altamont. If carcasses representing local species become available, for example the American kestrel or red tailed hawk, and are in sufficient numbers for statistical analysis, they will be incorporated into the field activities. Generally, any species that is considered small (or moderately small) can be used in the field trials. Local species of interest, although preferred, are not available in the numbers required for this project. However, mixing species from the same size class is acceptable.

Field Measurements and Data Collection

The following information will be collected by the PFMs during each observation of a specific string:

- a) String number
- b) Block number
- c) Date
- d) Temperature
- e) Precipitation amount since last observation (inches)
- f) Total number of birds/bats on the plot
- g) Position of bird/bats or significant parts of birds/bats (distance and bearing from closest turbine and GPS location)
- h) Number of birds/bats that show sign of vertebrate scavenging (i.e., torn apart)
- i) Number of birds/bats with no visible sign detected (i.e., dragged outside of search area, blown away, removed completely, etc.)
- j) Description of remaining carcasses and carcass parts
- k) Vegetation type (genus and species), vegetation height (mm), and vegetation color.
- l) Visibility class (see discussion below).
- m) Topography

Items (j), (k), (l), and (m) above will be recorded for each individual carcass on the ground. Grass height measurements will be taken using a metric ruler. If multiple carcasses are found within a uniform vegetation type and height, then a single measurement will be taken for all individuals in the group. Topography metrics will include whether carcasses are placed (1) on top of a ridge line, (2) on the side of a ridge, (3) on flat ground, (4) on a ridge saddle, or (5) in a ridge depression.

In addition to the above, the PFMs will assign, to the degree possible, a visibility class indicator for (a) the entire string, and (b) each carcass location. Visibility class is a metric for characterizing the types of ecological variation that influences survey error rates at wind developments. Visibility obviously impacts all aspects of the survey error rate components (both human and ecological), and is a surrogate metric for site-specific variability that can be used within a formal experimental design framework. The Pennsylvania Game Commission (PGC) established four visibility classifications, recommending¹⁴ that survey error rates be estimated for each:

- Class 1 (easy): Bare ground 90% or greater; all ground cover sparse and 6 inches or less in height (i.e. gravel pad or dirt road).
- Class 2 (moderate): Bare ground 25%-89%; all ground cover 6 inches or less in height and mostly sparse.
- Class 3 (difficult): Bare ground 25% or less; 25% or less of ground cover over 12 inches in height.

¹⁴ Pennsylvania Game Commission (PGC). 2007. Pennsylvania Game Commission wind energy voluntary agreement. Pennsylvania Game Commission, Harrisburg, Pennsylvania.

- Class 4 (very difficult): Little or no bare ground; more than 25% of ground cover over 12 inches in height.

The following information will be collected by the observers when marked carcasses are found at an individual string:

- a) String number
- b) Block number
- c) Date
- d) Observer name (or ID)
- e) Total number of birds/bats observed
- f) Number of birds/bats observed outside of search area
- g) GPS location
- h) Distance and bearing to closest turbine (including turbine ID or number)

Using the distance and bearing measurements, the PFM will, subsequent to the observers visit, correlate the found carcasses with the detailed information collected by the PFM.

All recorded data will be transferred to an Excel file by the PFM. The field sheets and Excel file will be transferred to the Principal Investigators, who will conduct an independent review of the Excel file to ensure that no transcription errors have occurred.

Field Study Personnel

The PFMs will have full responsibility for the day-to-day activities required by the field study. The primary PFM is Brian Karas, a part-time employee of EcoStat, Inc. He will be assisted by Loan Tran, a part-time employee of EcoStat, Inc.

The Point Reys Bird Observatory (PRBO) will supply field biologists to act as observers. The PRBO staff will act as the blind observers, and visit each string in the study approximately three times.

Pilot Study

Prior to initiation of the main study, a pilot study will be implemented. The pilot study will be used to address key issues affecting the study procedures and will allow the PFMs to test and refine methods for carcass placement, daily tracking of carcasses, refine data collected by the PFMs, transportation issues, and other practical matters. The pilot study will replicate all procedures planned for the full study (described above), and will use the same types of bats and birds planned for the full study. Information obtained from the pilot study will be used to refine the full study activities and logistics. Specific issues of interest include the following:

- 1) Expected length of time birds and bats remain un-scavenged.
- 2) Time needed by the PFM to place carcasses, count remaining carcasses, take measurements, and record information.

- 3) Determination of the searcher speed or searcher time per some unit of distance to monitoring strings.
- 4) Coordination among the PRBO observers and PFMs.
- 5) Number of strings that can be simultaneously evaluated.
- 6) Estimation of observation intervals over the course of six weeks.
- 7) Estimation of observation intervals to ensure that both young and older carcasses are observed.
- 8) Estimation of the total effort for the current design; and evaluation of any needed changes based on the cost estimates.
- 9) Evaluation of carcass placement approaches (random, clustered, etc.).
- 10) Evaluation of best time of day for the PFMs to check each string.

The pilot study will include a full block (six strings). The pilot information will be evaluated for data quality. If the information from the pilot study is deemed of sufficient quality, the information will be used in the full data analysis. The pilot study block is considered part of the total five block project (leaving four remaining blocks). The pilot study will be run for the entire six week period. After the pilot study data have been compiled, the project will stop, and will continue only after a full evaluation and interpretation of the lessons learned from the pilot information. This break is anticipated to last approximately one week.

Interactions with Ongoing Altamont SRC Study

The CalWEA study can interact with the on-going SRC study in the several ways. The Altamont MT can:

- 1) Act as blind observers for one or more strings, thus providing additional evidence that can be used to evaluate observer error.
- 2) Provide fresh carcasses representing local species of interest, including the American kestrel and red tailed hawk.
- 3) Provide coordination support for the selection of strings and blocks.
- 4) Provide additional support by characterizing ecological characteristics of the strings such as measuring grass height, type of vegetation, etc.
- 5) Provide support with site transportation, field supplies and equipment.

At this time, discussions concerning support by the Altamont MT have been positive. Details concerning any support provided by the Altamont MT will be finalized at a later date.

Data Analysis

Analysis of the data resulting from the field trials will be used to evaluate the multiple aspects of survey error. Data analysis will consist of the following components:

- 1) Comparison of mortality estimates generated by equations 1 – 5 on page 3 with the true mortality.
- 2) Evaluation of the variation in carcass removal rates as a function of site-specific conditions.
- 3) Evaluation of the relationship between observer error and site-specific conditions.
- 4) Development of new stochastic models (such as the attached example) that incorporate time-dependent relationships between carcass removal and observer error.

All of the terms in equations 1-5 can be computed from the information collected during the field studies. Therefore, for any observation date (n=84) a comparison of the estimated true mortality based on the equations can be directly compared to the actual or true mortality based on observations by the PFMs. The differences between the estimated and observed true mortality will be presented in simple tables (i.e., average difference by equation) and graphical forms (e.g., histograms of differences).

A carcass removal function for both birds and bats can be derived for each string (n=28) in the study. Figure 1 illustrates the expected shape of the resulting function. A variety of statistical techniques are available for deriving a statistical model using the field data. Classic survival model and hazard function¹⁵ equations can be used to generate a carcass removal curve for each string. Survival analysis is effectively a time to event analysis. The term survival analysis is used predominately in biomedical sciences where the interest is in observing time to death either of patients or of laboratory animals. Time to event analysis has also been used widely in the social sciences where interest is on analyzing time to events such as job changes, marriage, birth of children and so forth. In the case of this project, the event is the removal of a carcass from the ground, or the expected time a carcass will remain on the ground at any string. The mathematics of these models are not presented here, but numerous model forms with multiple parameters are available in the literature. Most of the available statistical software have modules for estimating the parameters of the hazard functions. Parameters of the hazard function can be linked to specific environmental characteristics, and an evaluation of the hazard rate and the relationship to environmental metrics can be evaluated. The parameters of the resulting models will be displayed in table form. A graphical presentation of the removal curves can be used to display the variability in removal rate within the data base.

Success Measures

This project will be considered successful if the following goals are achieved:

- 1) Comparison of the existing mortality equations provides insight into the most accurate equations under varying environmental conditions.

¹⁵ Kleinbaum, D. G., and Klein, M. 2009. *Survival Analysis*, 2nd ed., Springer-Verlag. New York, New York. 196 pps.

- 2) Data generated from the project are of such quality that guidance for implementing site-specific studies leading to effective mortality adjustment procedures can be developed.
- 3) Peer-reviewed publications are generated that enhance the existing state of the science.
- 4) Effective communication of the project findings is undertaken.
- 5) Observational data at the planned wind turbine strings are obtained in a cost-effective manner within the timeframe of the project.

1 Introduction

Let's build a stochastic statistical model for the death of birds and the subsequent removal (by scavengers) or discovery (by Monitoring Teams) of their carcasses, with the aim in mind of making inference about death rates from counts.

Initially we will consider a single site or locus (depending on the context this might be a single windmill or a group of nearby windmills), a single type or species of bird or bat, and we will model time (in days) as a continuous variable. Later we will consider multivariate data for multiple avian types or species; multiple loci with geographical information about their locations; and will aggregate the data to integer-labeled convenient reporting time periods, such as days or weeks. At first we will take bird death-rates and removal-rates (by scavengers) to be constant—without seasonal or diurnal cyclicities and without trend. We will also assume perfect searches—no missed carcasses, no false positives, no ambiguous partial carcasses. All these simplifications may be removed later.

1.1 The Model

If mortality counts in non-overlapping time intervals are independent, and if we ignore or forbid multiple simultaneous kills, then it follows from probability theory (the “law of small numbers”) that the number $\mathcal{N}(a, b]$ killed during any time interval $a < t \leq b$ has a Poisson distribution

$$\mathcal{N}(a, b] \sim \text{Po}(M(a, b])$$

whose mean, the mean cumulative mortality count for the interval,

$$M(a, b] = \int_a^b m_t dt$$

is the integral of the instantaneous mortality rate m_t . Let $r_{s,u}$ denote the instantaneous removal (or scavenging) rate at time u of a carcass that died at time $s < u$ (this may depend both the time of day, through u , and the freshness of the carcass, through $u - s$), so during each short interval $(u, u + \epsilon]$ of length $\epsilon > 0$, a carcass that died at time $s < u$ has a probability of approximately $\epsilon \times r_{s,u}$ of being removed by scavengers. Assume (for now) that these removals are independent. Then, the (random) number of carcasses present at any time t also has a Poisson distribution

$$\mathfrak{C}_t \sim \text{Po}(C_t),$$

with rate

$$C_t = \int_{-\infty}^t m_s \exp \left\{ - \int_s^t r_{s,u} du \right\} ds, \quad (1)$$

the accumulation of all those carcasses that arrive at earlier times $s < t$ and elude scavenging until after time t . This Poisson-valued stochastic process has been long studied in the population dynamics world (Kendall, 1948), particularly the stationary case in which m and r are taken to be constant, the so-called “linear death process with immigration.”

It and the related \mathcal{N} can be constructed and simulated (and many of their properties devined) beginning with a unit-rate Poisson random measure $\mathfrak{N}(dt dx dy)$ on $\mathbb{R} \times \mathbb{R}_+ \times (0, 1]$ in the form

$$\mathcal{N}(a, b] = \mathfrak{N}(\{(s, x, y) : a < s \leq b; 0 < x \leq m(s); 0 < y \leq 1\}) \quad (2a)$$

$$\mathfrak{C}_t = \mathfrak{N} \left(\{(s, x, y) : -\infty < s \leq t; 0 < x \leq m(s); 0 < y \leq \exp \left\{ - \int_s^t r_{s,u} du \right\}\} \right) \quad (2b)$$

(see Wolpert and Taqqu, 2005, for the general idea of “upstairs” modeling, and Figure (1) below for an illustration).

2 Stationary Case

In the special case of constant carcass mortality and removal rates $m_s \equiv m$ and $r_{s,u} \equiv r$, the stochastic process $\mathfrak{C}_t \sim \text{Po}(C_t)$ (the number of carcasses present) is *stationary*, *i.e.*, has the same probability distribution at all times. It has representation (see Equation (1))

$$\mathfrak{C}_t = \mathfrak{N} \left(\{(s, x, y) : -\infty < s \leq t; 0 < x \leq m; 0 < y \leq e^{-(t-s)r}\} \right) \quad (3)$$

with constant expectation

$$\mathbb{E}[\mathfrak{C}_t] = C_t = \int_{-\infty}^t m e^{-(t-s)r} ds = \frac{m}{r} \quad (4a)$$

and with covariance function

$$\mathbb{V}[\mathfrak{C}_s, \mathfrak{C}_t] = \frac{m}{r} e^{-r|t-s|} \quad (4b)$$

that depends on time only through the time lag $|t - s|$. The waiting time W_i that a carcass spends until it is scavenged has an Exponential $\text{Ex}(r)$ distribution with survival function

$$\mathbb{P}[W_i > w] = e^{-rw}, \quad w > 0$$

and mean $\mu_W = \mathbb{E}[W_i] = r^{-1}$.

2.1 Discrete Time

Let $\mathfrak{C}_{i\Delta}$ be \mathfrak{C}_t evaluated at integer multiples $t = i\Delta$ of some fixed time lag Δ (perhaps a day, week, or month); from Equation (3) we can show the recursive relation

$$\mathfrak{C}_{i\Delta} = Y_i + T_i \quad (5a)$$

where the independent random variables Y_i, T_i have distributions:

$$Y_i \sim \text{Bi}(\mathfrak{C}_{(i-1)\Delta}, S) \quad (5b)$$

$$T_i \sim \text{Po}\left(\frac{m}{r}(1-S)\right) \quad (5c)$$

with $S = e^{-r\Delta}$ the probability of *not* being removed by scavenging in a single time period. One can interpret Y_i as the number of carcasses remaining from “Yesterday”, period $i-1$ (or earlier), and T_i as the number of new carcasses not removed by scavengers earlier “Today” (period i). If S is close to zero then virtually no carcasses remain from one period to the next. In this case observations $\mathfrak{C}_{i\Delta} \approx T_i$ are nearly independent, but naïve methods will grossly underestimate m because of scavenging *during* the period of observation. If S is close to one then counts $\mathfrak{C}_{i\Delta} \approx Y_i$ will change little from period to the next, as a relatively few carcasses are removed each period and about the same number of new ones appear. In the more interesting intermediate case, where S is not too close to either zero or one, we have a chance to estimate both S and m from successive counts $\mathfrak{C}_{i\Delta}$.

2.2 Stationary Inference

From a long series of observations $\mathfrak{C}_\Delta, \mathfrak{C}_{2\Delta}, \mathfrak{C}_{3\Delta}, \dots$ we can estimate $E[\mathfrak{C}_t] = m/r$ as the sample mean (see Equation (4a)) and then S from the sample lag- Δ autocorrelation (using Equation (4b)), which together determine the mortality rate m . A Bayesian reference analysis would begin with a joint reference prior distribution (Bernardo, 1979; Berger and Bernardo, 1992; Berger, Bernardo and Sun, 2009) for m and r and construct the likelihood function for m, r for the observed counts $\{\mathfrak{C}_{i\Delta}\}$, then generate posterior and predictive distributions using conventional numerical methods such as MCMC. Because we expect stationarity to be overly restrictive, we first consider a more flexible model before implementing methods for inference.

3 Weibull Models for Variable Scavenging Rates

Even if mortality and removal rates are stationary over time, it is natural to expect that the scavenging rate $r_{s,u}$ may in fact depend on the age ($u-s$) of the carcass. Fresher carcasses, with $(u-s)$ small, may be preferred by capable and discriminating predators, while less fresh carcasses may be easier to find. A simple way to accommodate this possibility is to set the rate

$$r_{s,u} = r\alpha(u-s)^{\alpha-1} \mathbf{1}_{u>s} \quad (6)$$

to be proportional to a power of $(u - s)$; positive powers ($\alpha > 1$) indicate increasing removal rates as carcasses age, while negative powers ($0 < \alpha < 1$) indicate decreasing rates. Under this model the waiting time W_i a carcass spends until scavenging has a *Weibull* $We(\alpha, r)$ probability distribution with survival function

$$P[W_i > w] = e^{-rw^\alpha}, \quad w > 0$$

with mean $\mu_W = E[W_i] = r^{-\alpha^{-1}}\Gamma(1 + \alpha^{-1})$. Again \mathfrak{C}_t can be constructed and simulated using a unit-rate Poisson random measure as in Equation (1), now with

$$\mathfrak{C}_t = \mathfrak{N}\left(\{(s, x, y) : -\infty < s \leq t; 0 < x \leq m; 0 < y \leq \exp\{-r(t-s)^\alpha\}\}\right), \quad (7)$$

The projection onto two-dimensional set $\{(s, y)\}$ is shown in Figure (1), with blue solid

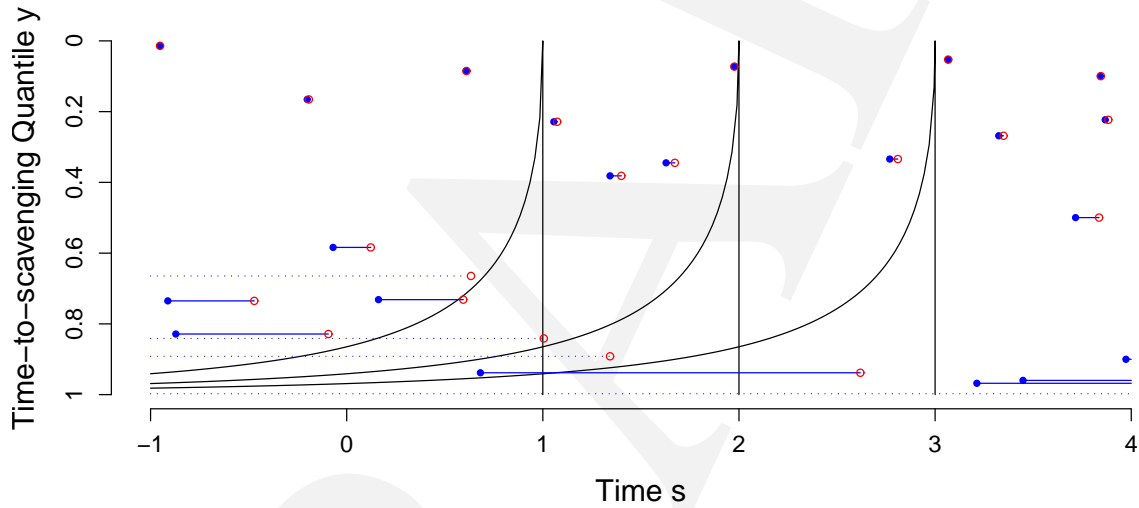


Figure 1: Illustration of \mathfrak{C}_t from Equation (7) for $t = 1, 2, 3$.

dots (indicating mortality events) connected by horizontal lines to red open dots (indicating scavenging events) for each carcass. Waiting times (in days) W_i until carcasses are scavenged are just the lengths of the horizontal lines. In this illustration they have the Weibull $We(0.5, 2)$ distribution with mean $E[W_i] = 0.5$; with average mortality rate $m = 4$, this leads to expected numbers $C_t = 2$ of carcasses at every time t . Vertical position y indicates the quantile of W_i for this distribution. Note that none of the thirteen (of 25) carcasses in this simulation with W_i below the population median (0.12), *i.e.*, in the top half of the figure with $y < 0.50$, was observed at times $t = 1, 2, 3$ (*i.e.*, fell into one of the three tent-shaped regions), even though several were killed (and subsequently scavenged) during those days.

Carcass counts \mathfrak{C}_t ($\mathfrak{C}_1 = 4$, $\mathfrak{C}_2 = 2$, $\mathfrak{C}_3 = 1$) are indicated by either the number of filled dots in the tent-shaped regions beneath the rising curve ending at t or, equivalently, by the

number of horizontal lines crossing the vertical segment at t , corresponding to carcasses whose mortality preceded and whose scavenging followed time t . Dotted horizontal lines indicate carcasses whose mortality occurred prior to the window of times shown in the figure.

From this geometric representation, properties such as mean and covariance may be computed easily as needed. For example, the expected count of carcasses on the ground at any time t and the covariance of counts at times s and t are given respectively by

$$\mathbb{E}[\mathfrak{C}_t] = C_t = \int_{-\infty}^t m e^{-r(t-s)^\alpha} ds = m\mu_W = m\Gamma(1 + \alpha^{-1})/r^{\alpha^{-1}}, \quad (8a)$$

$$\mathbb{V}[\mathfrak{C}_s, \mathfrak{C}_t] = \frac{m}{\alpha} r^{-\alpha^{-1}} \Gamma(\alpha^{-1}, r|t-s|^\alpha) \quad (8b)$$

where $\Gamma(a, z)$ is the complimentary incomplete Gamma function (Abramowitz and Stegun, 1964, §6.5.3). Again, as with any stationary distribution, the mean is constant and the covariance depends on time only through the lag $|t-s|$. These reduce to (m/r) and $(m/r)e^{-r|t-s|}$ respectively as in Equation (4) for $\alpha = 1$, as of course they must.

One may still view the carcass count at the i^{th} period

$$\mathfrak{C}_{i\Delta} = Y_i + T_i$$

as the sum of today's arrivals T_i and those remaining from yesterday Y_i , but for $\alpha \neq 1$ the changing rate of scavenging as carcasses age precludes the simple Markov modeling of Equation (5). For example, with $\alpha = 0.5$ (as in Figure (1)) we would have $\mathbb{P}[W_i > w] = e^{-r\sqrt{w}}$, so the chance of being scavenged in the next hour falls like the square root of the carcass age, and (unlike Equation (4a)) the expected number is $C_t = 2m/r^2$. This makes inference more subtle for the Weibull model.

3.1 Weibull Inference I: Study Carcasses

Inferring both Weibull parameters r, α from count data $\mathfrak{C}_{i\Delta}$ would be tough with moderately large gaps Δ ; for this reason an experimental design (Warren-Hicks, 2010, *pp.* 11–13) was constructed with both (nearly) periodic observations of \mathfrak{C}_{t_i} at intervals of approximately $\Delta \approx 30$ –45 days by Monitoring Teams, and additional daily recordings by the Study Director of the status of a fixed number of study carcasses placed intentionally on-site, intended in part to help reveal the scavenging rate $r_{s,u}$ or, under the Weibull model, the parameters α and r .

At each of several sites, the proposed experimental design entails placing a fixed number J of study carcasses at a fixed time (say, at $t = 0$) and recording their status each day for the following 30 days. If we could observe the exact time-to-scavenging $\{W_j\}_{1 \leq j \leq J}$ and view them as independent observations from the $\text{We}(\alpha, r)$ distribution, we could base inference

on the log likelihood function

$$\begin{aligned}\ell(\alpha, r) &= \log \prod_{j \leq J} [\alpha r W_j^{(\alpha-1)} e^{-r W_j^\alpha}] \\ &= J \log(\alpha r) + (\alpha - 1) \sum_{j \leq J} \log W_j - r \sum_{j \leq J} W_j^\alpha\end{aligned}$$

from which maximum likelihood estimates (MLEs) $\hat{\alpha}$, \hat{r} and standard errors or reference Bayesian posterior distributions $\pi(\alpha, r)$ may be calculated numerically.

When we do not observe W_j precisely but only the number of full days $\lfloor W_j \rfloor$ (W_j rounded down to the next lower integer $w_j \geq 0$) before scavengers remove the carcass, as in the proposed experimental design, then each observation $\lfloor W_j \rfloor = w_j$ contributes

$$\begin{aligned}\log \mathbf{P}\{\lfloor W_j \rfloor = w_j\} &= \log \mathbf{P}\{w_j < W_j \leq 1 + w_j\} \\ &= \log[e^{-r(w_j)^\alpha} - e^{-r(1+w_j)^\alpha}]\end{aligned}$$

to the log likelihood

$$\ell(\alpha, r) = \sum_{j \leq J} \log[e^{-r(w_j)^\alpha} - e^{-r(1+w_j)^\alpha}] \quad (9a)$$

$$= \sum_{j \leq J} \log(1 - e^{r[w_j^\alpha - (1+w_j)^\alpha]}) - r \sum_{j \leq J} w_j^\alpha \quad (9b)$$

(with a simple adjustment to accommodate any carcasses left unscavenged at the end of the last observation period). MLE estimates or reference posterior distributions for α and r are available from Equation (9); in either case this will improve dramatically the precision with which the parameters of interest such as the mortality rate m may be estimated using the Monitoring Team observations of natural (non-study) carcasses.

3.2 Weibull Inference II: Monitoring Team Observations

To do: Introduce Monitoring Team reported counts of non-study avian carcasses at irregular intervals of approximately 30–45 days; emphasize that irregularity is no obstacle, and show how to synthesize evidence from these data and from the study-carcass data from the Study Director’s daily observations, described above in Section (3.1).

4 Accommodating Imperfect Observations

To do: Introduce (for now) constant probability p that the Monitoring Team will observe an extant carcass (“proficiency”); show how this affects likelihood, and how study birds may offer evidence about the value of p .

5 Synthesizing Evidence from Diverse Terrains

To do: Introduce explanatory variables (grass height, weather, etc.) and simple (logistic) dependence of the proficiency p on some of these variables. Build hierarchical Bayesian model with exchangeable parameters m_j, r_j , etc. for different sites (indexed here by j); talk about “shrinkage” or “sharing strength.”

6 Discussion & Possible Extensions

To do: Discuss extensions and elaborations such as: Is there evidence of density dependence? Should we use study-carcass data to criticize (and perhaps change) the Weibull model? For example, removal rate might decrease initially and then rise... More suggestions from CalWEA?

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